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Report to the Chairman, Subcommittee on Oversight and Investigations, Committee on Energy and Commerce, House of Representatives

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AIR POLLUTION

Improved Atmospheric Model Should Help Focus Acid Rain Debate

GAO/RCED-90-14

GAO United States
General Accounting Office
Washington, D.C. 20548

Resources, Community, and
Economic Development Division

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November 3, 1989

The Honorable John D. Dingell
Chairman, Subcommittee on
Oversight and Investigations
Committee on Energy and Commerce
House of Representatives

Dear Mr. Chairman:

As you requested by letter and on the basis of subsequent discussions with your office, this report discusses the progress of the National Acid Precipitation Assessment Program's (NAPAP) research to determine acidic deposition's effects on man-made and natural resources. In particular, we closely examined NAPAP's progress in developing, applying, and evaluating the Regional Acid Deposition Model.

Unless you publicly release its contents earlier, we will make this report available to other interested parties 30 days after the date of this letter. At that time, copies of the report will be sent to appropriate congressional committees; the Director of Research at NAPAP; the Administrators of the Environmental Protection Agency and the National Oceanic and Atmospheric Administration; the Secretaries of Agriculture, Energy, and the Interior; and the Director of the Office of Management and Budget.

This work was performed under the general direction of Richard L. Hembra, Director, Environmental Protection Issues, who may be reached at (202) 275-6111. Other major contributors to this report are listed in appendix III.

Sincerely yours,

J. Dexter Peach

J. Dexter Peach
Assistant Comptroller General

Executive Summary

Purpose

Acid rain continues to be one of the most hotly debated environmental issues facing the nation. Much of the disagreement concerns the level of controls to be imposed on emissions of sulfur dioxide and nitrogen oxides, the precursors of acid rain. To provide a better base of information for decision making, in 1980 the Congress authorized an interagency research effort, the National Acid Precipitation Assessment Program (NAPAP), to study and report by 1990 on the causes and effects of acid rain.

One important aspect of this research effort is the Regional Acid Deposition Model (RADM). Designed to simulate the complex processes by which air emissions are transported, converted, and deposited as acid rain, RADM is supposed to estimate changes in deposition that occur in response to emission controls. Understanding this relationship should also facilitate examination of the relationship between control costs and actual reductions in acid rain.

The chairman of the Subcommittee on Oversight and Investigations, House Committee on Energy and Commerce, asked GAO to review NAPAP's progress in developing, applying, and evaluating RADM.

Background

Acidic deposition, commonly referred to as acid rain, occurs when sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emitted from coal-fired power plants, motor vehicles, and other man-made and natural sources are transformed into acid compounds. These compounds may then fall hundreds of miles from their source of emission in either dry form or as precipitation. While the causes of acidic deposition are relatively well understood, its effects on the environment are less certain. In addition, the precise relationships between levels of emissions and deposition and between sources of emissions and locations of deposition have not yet been established. RADM's intended purpose is to reduce the uncertainties surrounding these questions.

NAPAP plans to raise the general level of scientific understanding regarding the acidic deposition phenomenon and to help decision makers now considering proposals to reduce emissions, through publication of its State of Science/Technology reports and a final integrated assessment. The State of Science/Technology reports are expected to provide relevant technical information on the causes and effects of acidic deposition. The integrated assessment is designed to assist policy makers and the public in evaluating key questions concerning acidic deposition.

Acidic deposition control bills have been introduced in the 101st Congress that would require at least a 10-million-ton reduction in annual SO_2 emissions. Each of these bills proposes a two-phased approach to SO_2 controls.

Results in Brief

NAPAP completed developmental work on RADM in January 1989, 2 years beyond its original target date. In addition, as of May 1989, portions of RADM's assessment applications had been delayed about 10 weeks. These delays, however, do not seem to have had a dramatic, adverse effect on the scheduling of research supporting NAPAP's final assessment. Even though RADM will not be formally evaluated until at least 1992, NAPAP plans to use analyses from the model extensively in the final report. NAPAP officials believe that preliminary evaluations, including an initial trial run and two peer reviews, have laid a good foundation for RADM's credibility.

Under a two-phased emission control program like those introduced in the current Congress, RADM results could be useful in helping to establish controls for phase II. The Congress need not wait, however, for RADM results to set phase I controls. If phase I controls are reductions of 25 percent or less of total SO_2 emissions as is currently proposed, then reductions would be small enough that RADM's complete depiction of atmospheric processes would not be needed to design and implement a scientifically sound interim policy. NAPAP experts are confident that current atmospheric models would suffice to guide phase I emissions reductions.

Principal Findings

NAPAP's Progress in Developing, Applying, and Evaluating RADM

Originally, RADM was to have been developed and documented by January 1987. However, NAPAP officials suggested that RADM's original milestones were overly optimistic because development of the model was a larger, more complex task than expected. As a result, the version of RADM to be used in the assessment was not provided to NAPAP until January 1989.

One of RADM's applications in the assessment is to estimate future deposition based on future emissions scenarios. A disagreement between EPA and the Department of Energy (DOE) over the extent to which clean coal

technologies will be adopted by the utility industry delayed agreement on emissions projections necessary as input for these RADM analyses. Because these input data were unavailable, portions of RADM's applications schedule have fallen behind by as much as 10 weeks. As a result, RADM analyses originally scheduled for completion in October 1989 have had to be reformatted and rescheduled for delivery in December 1989 and February 1990. Despite this delay, NAPAP officials remain confident that the integrated assessment can be completed on time.

RADM's evaluation has two objectives: to determine how accurately the model estimates acidic deposition and to ensure that the model represents the best understanding of atmospheric science. NAPAP officials believe that the original deadlines set for evaluating RADM were unrealistic; therefore, the timetable for completing the evaluation has slipped to 1992. Despite delays in its evaluation, NAPAP officials remain convinced of RADM's usefulness and plan to incorporate RADM-assisted analyses in the assessment. The model has already undergone a significant amount of testing, including a successful simulation of actual deposition from two sets of field observations. In addition, peer reviews conducted in 1985 and 1987 found RADM to be a major improvement in regional modeling. For these reasons, NAPAP officials are relatively confident of RADM.

RADM's Importance to Emission Control Decisions

Several of the atmospheric phenomena that contribute to acidic deposition are too complex for previous models. Unlike earlier models, however, RADM takes into account several of these complexities, such as the chemical conversion of SO_2 and NO_x to acidic compounds.

Because RADM should be able to account for these complexities, it is likely to be able to estimate with greater accuracy than previous models the changes in acidic deposition that can be expected as a result of various levels of emissions reductions. This information could be useful for setting targets for emissions reductions. RADM's potential to define source-receptor relationships could also be useful in deciding whether and where to concentrate controls. Finally, because RADM should depict interactions among different pollutants in the atmosphere, it could allow policy makers to avoid inadvertently worsening one pollution problem by actions designed to control another. However, because of the analysis time lost due to the EPA-DOE impasse over future emission estimates, the task group leader is uncertain of the extent to which studies including multiple pollutants can be completed for inclusion in the assessment.

Current Congressional proposals to control acidic deposition envision beginning with SO_2 reductions of 3 million to 6 million tons, with controls gradually increasing to at least 10 million tons. Scientists agree that initial SO_2 reductions could proceed without benefit of RADM-based analysis or completion of the NAPAP final report on acidic deposition. As long as the initial SO_2 reduction level is relatively small, experts concur that changes in the atmosphere that would result from those emissions reductions would be small enough that current air quality models could guide phase I controls. Interim controls contained in current proposals would end in the 1994-96 time frame—after that time RADM's evaluation should be completed and more complete effects data should become available. Final emissions reduction decisions could then be based on more authoritative estimates of reductions in acidic deposition and its damage that should result from emissions controls.

Recommendations

GAO makes no recommendations in this report.

Agency Comments

GAO discussed the factual material contained in this report with NAPAP officials and incorporated their comments where appropriate. As requested by the chairman, GAO did not obtain official agency comments on a draft of this report.

Contents

Abbreviations

AREAL	Atmospheric Research and Exposure Assessment Lab
ASRL	Atmospheric Science and Research Lab
DOE	Department of Energy
DOI	Department of the Interior
EPA	Environmental Protection Agency
GAO	General Accounting Office
NAPAP	National Acid Precipitation Assessment Program
NOAA	National Oceanic and Atmospheric Administration
NO_x	nitrogen oxides
RADM	Regional Acid Deposition Model
SO_2	sulfur dioxide
SOS/T	State of Science/Technology
USDA	U.S. Department of Agriculture

Introduction

Acidic deposition, commonly referred to as "acid rain,"[1] is one of the most complicated issues confronting U.S. policy makers. It is one of the nation's dominant air quality issues and a primary focus of attempts to amend the Clean Air Act. As yet, a clear consensus on an appropriate course of action has not evolved. Although the international scientific community increasingly turned its attention to the phenomenon in the last decade, a number of disputes remain.

Considerable debate exists over the linkages between emissions, observed damages, and responsibilities for dealing with the problem. Acidic deposition has been linked to a number of environmental problems, including (1) declining fish populations in the northeastern United States, southeastern Canada, Sweden, and Norway; (2) forest damage in West Germany, the eastern United States, and Canada; and (3) material damages, such as building erosion. The primary sources of the emissions that may be causing much of this damage, in many instances, are thought to be hundreds of miles away. For example, sulfur dioxide emissions from older coal-burning power plants in the Midwest are suspected of contributing to damage to aquatic systems in New York, New England, and eastern Canada. Central issues in this debate are:

- What is the extent of damage attributable to acidic deposition?
- What controls should be implemented to contain or reverse this damage?
- Who should pay for the controls needed to reduce emissions?

Responding to the need for scientific information regarding the precise effects of acidic deposition and how to control it, the Congress created the National Acid Precipitation Assessment Program (NAPAP) in 1980. NAPAP plans to complete its research within the 10-year congressionally mandated period, culminating in publication of an integrated assessment of current knowledge of acidic deposition by September 1990.

To help address some of the key scientific issues associated with acidic deposition, NAPAP developed a unique tool—the Regional Acid Deposition Model (RADM). RADM's purposes are to (1) simulate the chemical transformation, transport, and deposition of acidic deposition and (2) help decision makers understand potential impacts of various control program scenarios.

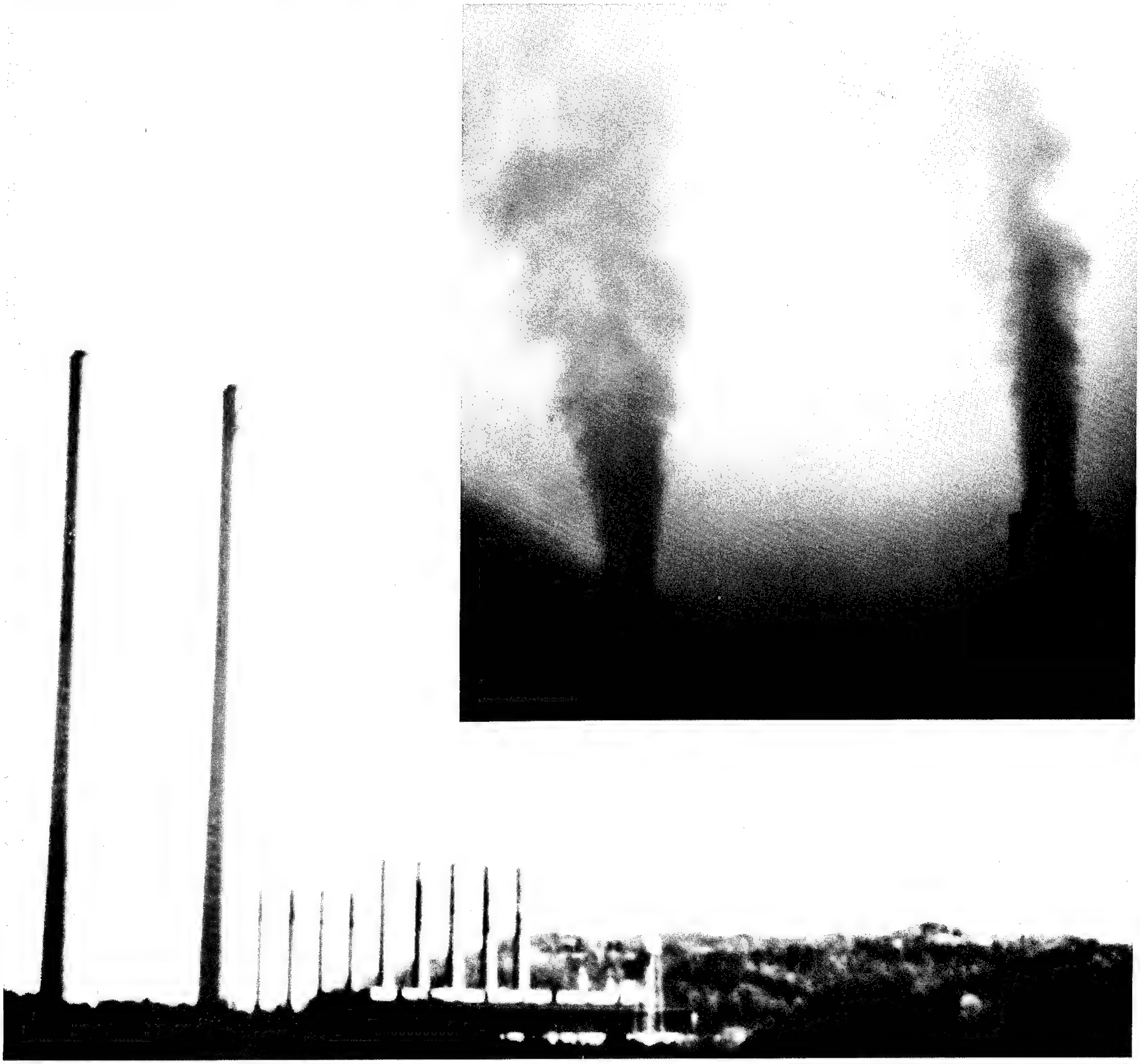
[1]Over time, several terms have been used to describe this phenomenon, including acid rain, acid precipitation, acid deposition, and acidic deposition. For purposes of this report, we use the more technically correct term, acidic deposition, which refers to the deposition of acidic material in both wet and dry forms.

Science of Acidic Deposition

Acidic deposition forms when sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emitted from coal-fueled power plants, motor vehicles, and other man-made and natural sources are transported and transformed in the atmosphere and return to earth, sometimes hundreds of miles downwind, as acidic deposition. This deposition can be in wet form, such as rain and snow, or dry form, such as small particles and gases. Wet and dry sulfur deposition constitute roughly equal parts of total acidic deposition. Transport distances of acidic deposition vary, with wet deposition typically carrying farther downwind from its sources than dry deposition.

Many United States and international scientists have reached substantial agreement on the causes of acidic deposition. For example, as seen in figure 1.1, SO_2 gas emissions have been identified as major sources of acidic deposition. Conversely, scientific verification of acidic deposition's effects on aquatic ecosystems, forests, crops, and structures is far from complete. Figures 1.2 and 1.3 illustrate damage to trees and statuary that some have attributed to acidic deposition, although evidence is far from conclusive.

Figure 1.1: Sulfur Dioxide Being Emitted From the Kingston Power Plant in Tennessee



Seen through a special camera filter (inset), SO_2 emissions from tall stacks such as these have been identified as major sources of acidic deposition hundreds of miles away.

Photo used by permission of the U.S. Congress, Office of Technology Assessment.

Figure 1.2: Dead and Dying Red Spruce at Camel's Hump in the Green Mountains of Vermont

Scientific investigations of tree death and growth decline cannot yet confirm or rule out acidic deposition as a contributor to the observed damages.

Photo used by permission of the U.S. Congress, Office of Technology Assessment.

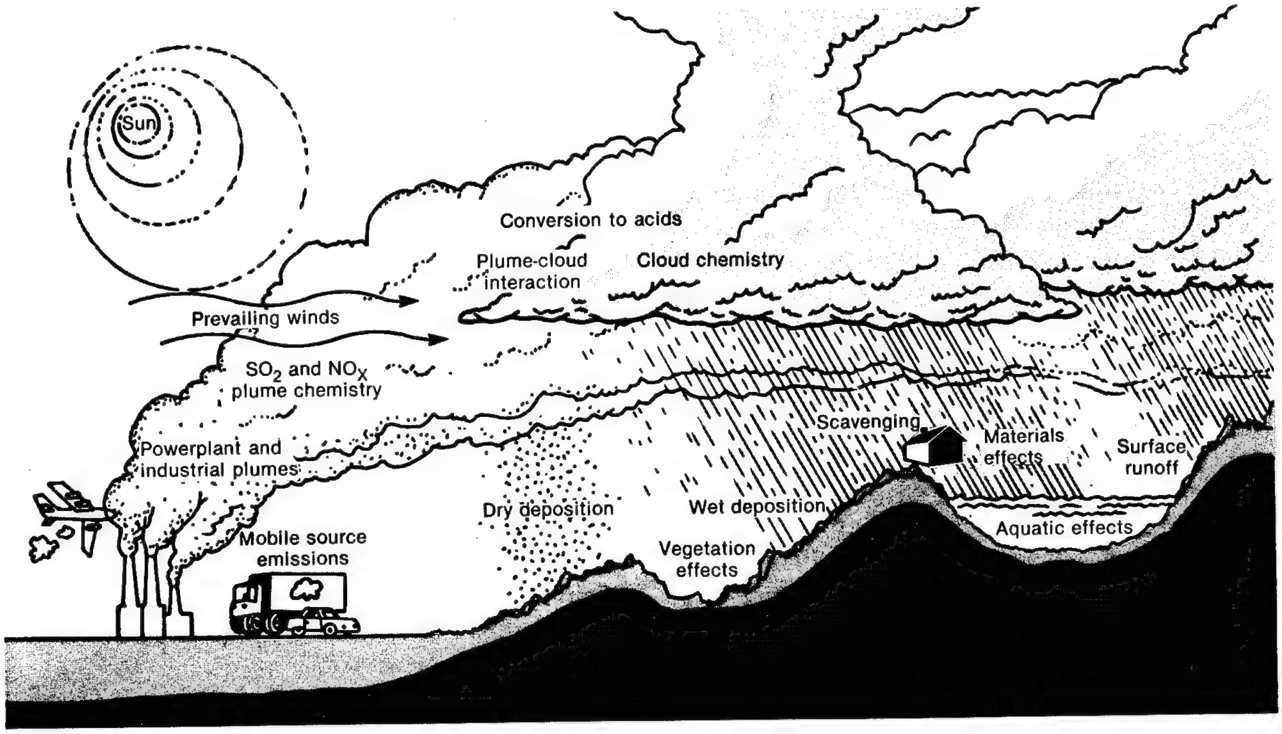
Figure 1.3: Corroded Statues in a Kentucky Cemetery

While acidic deposition and natural weathering have helped erode both the marble statues shown, scientific evidence is inconclusive as to the precise effect of acidic deposition on stone structures.

Photo used by permission of the U.S. Congress, Office of Technology Assessment.

NAPAP research findings are expected to address many of the questions currently surrounding the entire process of acidic deposition, its causes, extent, and effects. Illustrated in figure 1.4, this process encompasses the atmospheric cycle of $SO_2$and NO_x from emission points to their deposition on forests, aquatic systems, and man-made structures.

Figure 1.4: Acidic Deposition Cycle



While NAPAP attempts to address comprehensively the areas of the acidic deposition process, as represented in figure 1.4, RADM only models transformation, transport, and deposition (wet and dry).

NAPAP Organization

The Acid Precipitation Act of 1980 (Title VII of the Energy Security Act of 1980, Public Law 96-294) established the Interagency Task Force on Acid Precipitation to develop and implement NAPAP. As a 10-year program, NAPAP has a statutory responsibility to prepare comprehensive scientific, technological, and economic information to assist the President and the Congress in developing policies for the control of acidic deposition.

NAPAP's program of research is divided among seven task groups providing a comprehensive examination of the acidic deposition issue. Senior scientists from the funding agencies are appointed to serve as task

group leaders. These individuals are responsible for the direct oversight of NAPAP research and assessment activities. See appendix I for further detail on NAPAP organization.

NAPAP Assessment Reports

As of January 1989, almost $400 million of federal tax revenues has been invested in NAPAP-sponsored research since 1980; as a result, a large body of data on acidic deposition has been developed by several hundred technical experts. NAPAP task groups are now drawing upon this information to produce NAPAP's comprehensive assessment of the causes and effects of acidic deposition, and related control and mitigation strategies. NAPAP expects the assessment to be the most broadly based analysis of the issue ever undertaken.

NAPAP's assessment will be developed in two principal parts:

- 27 State of Science/Technology (SOS/T) reports, comprehensive analyses and discussions of relevant technical information prepared for specialist readers; and
- an integrated assessment, a structured compilation of policy-relevant technical information presented in a form suitable to assist policy makers and the public in evaluating the key questions concerning acidic deposition causes, effects, and control strategies.

NAPAP plans to complete its activities with publication of the integrated assessment in September 1990.

Although NAPAP-sponsored and other research has greatly improved understanding of many acidic deposition issues, NAPAP officials expect that uncertainties surrounding some important cause-effect issues will remain in 1990.[2]

State of Science/Technology Reports

The 27 reports, prepared by approximately 100 scientists, are planned to provide a comprehensive statement of available technical information concerning acidic deposition. The scope of the documents will include

- emissions, transport, transformation, air concentrations, and deposition of acidic and associated pollutants (Reports 1-8);

[2] The assessment will report NAPAP's best estimate of the level of confidence associated with its findings and hypotheses. See appendix II for discussion of NAPAP's scientific confidence levels.

- effects of acidic deposition and associated pollutants in all principal areas of concern: surface waters, forests, agricultural crops, exposed materials, human health, and visibility in the atmosphere (Reports 9-24); and
- control technology and economic evaluations (Reports 25-27).

According to senior NAPAP officials, these analyses will be subjected to several levels of review. For example, in addition to an interagency review by the NAPAP cooperating agencies, NAPAP plans to subject the SOS/T reports to peer review by independent scientists and to open review by all interested persons at an international meeting convened specifically to evaluate the reports in spring 1990. Following this review, the SOS/T reports will be published in final form in 1990. The reports will be used as the basis for the technical findings, using analysis, projection, and comparison methodologies that are the key elements of the integrated assessment. NAPAP's director believes the SOS/T reports when completed will constitute a significant contribution to the acidic deposition debate, since it is his understanding that these papers will be the first complete and fully reviewed summary of the subject. These papers, therefore, represent the first consensus statement of current scientific understanding and could be, according to the director, the most important contribution that NAPAP will make in understanding acidic deposition.

According to NAPAP, the emphasis on extensive external review of the SOS/T reports is intended to ensure that the integrated assessment is based on the broadest available, fully reviewed technical information, and thereby addresses, at least in part, past criticism of NAPAP procedures. Also, a lay summary of each of the SOS/T reports will be prepared and reviewed to ensure that the principal information is available to a wider audience of interested readers.

Integrated Assessment

The integrated assessment will focus the scientific information from the SOS/T reports on policy issues. These issues will be raised in a series of questions organized into five principal categories that address both present knowledge and future projections (table 1.1). NAPAP believes this structure develops a logical sequence of analysis intended to foster a well-founded evaluation of the benefits associated with various future emissions reduction scenarios.

Table 1.1: NAPAP's Five Key Assessment Questions

Present knowledge	
Question I	What are the adverse effects of acidic deposition and the relationship of these effects to acidic deposition/air pollutant concentrations?
Question II	What is the relationship between emissions and deposition/air pollutant concentrations?
Future projections	
Question III	What is the sensitivity to change for the relationship between emissions and (a) future economic, energy and technological conditions; (b) control costs; and (c) resulting deposition/air concentration levels?
Question IV	What are the estimates of future conditions (emissions, costs, deposition, and effects) with and without additional emissions reduction strategies?
Question V	What differences emerge from comparative evaluations of future scenarios?

The integrated assessment is intended to provide comprehensive scientific, technological, and economic information on the causes and effects of acidic deposition and on the effectiveness of various control measures in mitigating the adverse effects. According to NAPAP plans, questions I and II will provide a synthesis of the effects of acidic deposition and source-receptor relationships reported in the SOS/T reports. Question III is intended to serve as a bridge that links SOS/T findings to future projections by reporting results of a sensitivity analysis of key models. Question IV is planned to provide an analysis of illustrative future scenarios. The discussion planned in response to question V should compare key features and outcomes of the various scenarios. According to NAPAP, questions IV and V are the capstone of the integrated assessment, coordinating findings from diverse, but related, disciplines to afford assessment users a better understanding of the cumulative implications of future scenarios. The tools of the assessment are the data and models that reflect NAPAP's current scientific understanding of acidic deposition and its effects. These tools enable analysis and interpretation of the effects of various options and thus serve to link the assessment to its scientific underpinnings.

NAPAP plans call for the assessment to produce a range of outcomes of the emissions reduction strategies: deposition patterns, control costs, and effects. Comparisons of outcomes in question V are planned to be done by answering a set of subquestions regarding the level and timing of controls, their costs and effectiveness, and the environmental changes

expected to result from their implementation. NAPAP plans to report benefits of control strategies in three categories: (1) health-related, (2) economically denominated, and (3) conservation-related.

NAPAP's Regional Acid Deposition Model (RADM), designed to analyze the important relationship between sources of acidic deposition and actual deposition, is one of several models scheduled for application in the assessment. It has important roles in responding to questions II through IV, as well as in the analysis underlying future scenarios in question V.

Regional Acid Deposition Model

NAPAP developed RADM to help the assessment depict the transport, chemical transformation, and deposition of sulfur dioxide and nitrogen oxides. RADM is comprised of eight different components, or modules, each depicting a separate dimension of acidic deposition. When fed data that include meteorological conditions and emissions from multiple sources, RADM forecasts how weather and atmospheric chemistry could interact to deposit the emitted material over broad regions.

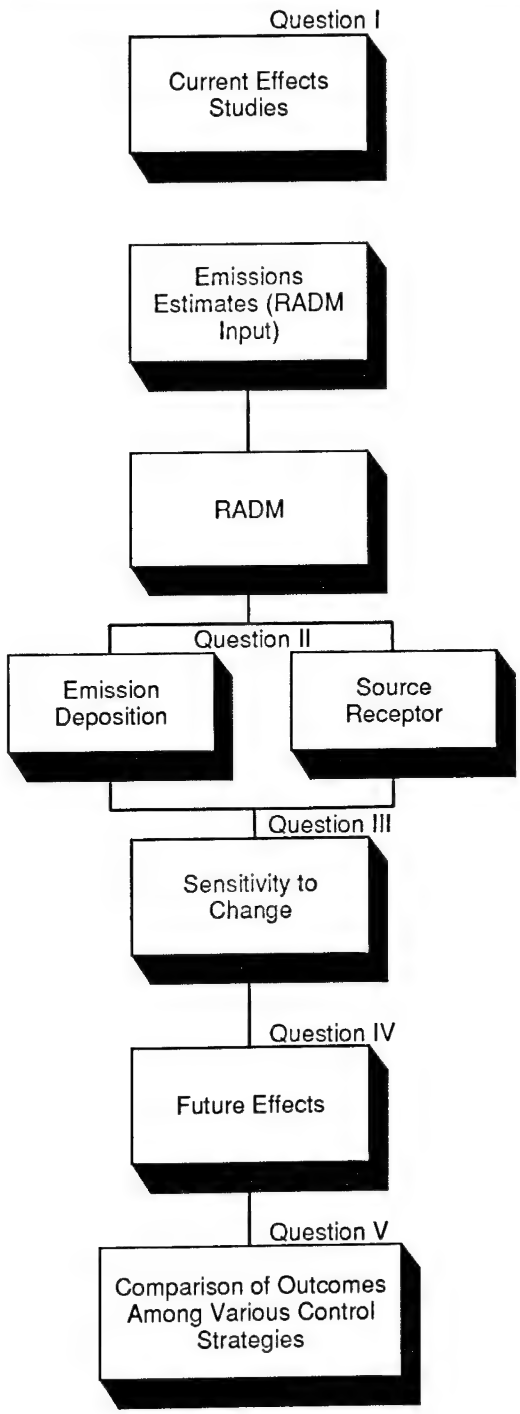
NAPAP plans to use RADM-assisted analyses in the assessment. For example, RADM output will be used to help assess

- the current relationship between acidic deposition and emissions, as well as current source-receptor linkages (assessment question II);
- how deposition and air concentrations might change when both sulfur and nitrogen emissions change (assessment question III); and
- how future changes in deposition could affect aquatics, terrestrials, materials, visibility, and human health (assessment question IV).

NAPAP also believes that RADM can play an important role in developing effective acidic deposition control programs through its ability to help identify source-receptor and emission-deposition relationships. Prior to RADM, neither the Congress nor EPA had tools available to allow a full understanding of what impact reductions in emissions would have on deposition. RADM and the integrated assessment, however, should provide decision makers with better information on which to base mitigation programs. Such information could lead to programs that concentrate on reductions of deposition and take into account the differential impacts of regional emission sources. Chapter 2 provides detailed information on the status of RADM.

Figure 1.5 depicts the integrated assessment and highlights RADM's role.

Figure 1.5: RADM's Role in NAPAP's Integrated Assessment



Previous GAO Reports

In response to continuing congressional interest in acidic deposition issues, we have issued five previous reports addressing varied acidic deposition concerns. In September 1981, we reported on the emerging debate over acidic deposition, the status of ongoing research, and the state of scientific understanding in The Debate Over Acid Precipitation: Opposing Views, Status of Research (EMD-81-131).

In December 1984, we summarized the state of knowledge concerning the causes and effects of acidic deposition and examined issues relating to initiation of controls in An Analysis of Issues Concerning "Acid Rain" (GAO/RCED-85-13). The report concluded that available scientific information neither proved nor disproved the need for controls.

In December 1985, we reviewed federal research efforts into acidic deposition effects on aquatic and terrestrial resources, and funding for federal acidic deposition research in Acid Rain: Federal Research Into Effects on Waters and Forests (GAO/RCED-86-7). We reported that initial NAPAP analyses indicated that some eastern U.S. lakes had already become acidic. We also identified 81 aquatic research projects, but only a limited number of forest effects projects since forest effects research did not emerge as a major issue until 1983.

In April 1987, we reported on NAPAP management in Acid Rain: Delays and Management Changes in the Federal Research Program (GAO/RCED-87-89). We found that NAPAP's interim assessment was delayed about 2 years and that NAPAP annual reports were also issued late and contained no policy recommendations. While some scientists and managers lauded the improved focus the new director of research position provided the program, we identified several remaining problems.

In December 1987, we reported on EPA efforts to develop RADM in Air Pollution: Information on EPA's Efforts to Control Emissions of Sulfur Dioxide (GAO/RCED-88-32). We found that RADM was encountering cost overruns and delays.

Objectives, Scope, and Methodology

In a May 19, 1987, letter, the Chairman, Subcommittee on Oversight and Investigations, House Committee on Energy and Commerce, expressed an interest in NAPAP's progress toward issuing its final integrated assessment. In particular, we agreed with the Chairman's office to review NAPAP's progress in developing, applying, and evaluating RADM.

We performed our work between August 1988 and August 1989 at

- the Washington, D.C., headquarters of EPA and DOE;
- NAPAP's Office of the Director in Washington, D.C.;
- offices of NAPAP's task groups in Washington, D.C.; Reston, Virginia; Arlington, Virginia; Research Triangle Park, North Carolina;
- office of RADM's project director at the State University of New York in Albany, New York;
- offices of New York State's Department of Environmental Conservation and Department of Law;
- the offices of the Electric Power Research Institute in Washington, D.C.; and
- the Washington, D.C., offices of relevant industry organizations.

We also interviewed officials of Ontario's Ministry of the Environment and the Atmospheric Environment Service, Environment Canada, as well as relevant environmental organizations.

To evaluate the timeliness of RADM development, we examined documents and files of ongoing NAPAP projects supporting RADM development and evaluation. These files included project schedules, budgets, staffing, and draft summaries. We also studied RADM peer review comments. We discussed RADM development with the NAPAP director, officials from NAPAP's Interagency Science Committee, Interagency Policy Committee; and staff from relevant task groups as well as RADM's project director and project officer. Our purpose in reviewing RADM documents and discussing RADM projects with appropriate officials was to establish the extent to which RADM could be delayed as a result of problems in scheduling RADM-related work.

The timeliness of the integrated assessment depends also on scheduling of effects groups' work. We therefore discussed progress of that work with senior NAPAP officials and task group members and examined NAPAP plans and documents.

To determine whether the Congress should await completion of RADM-based analyses before enacting acid rain legislation, we attempted to understand the results that could accrue from different proposed control programs, and the role that RADM could play in analyzing control proposals.

We performed our work in accordance with generally accepted government auditing standards. We discussed the factual information in the report with NAPAP officials during the course of our work and have incorporated their views as appropriate. However, as directed by the

requester, we did not obtain official agency comments on a draft of this report.

Status of RADM Development, Applications, and Evaluation Activities

NAPAP began work on RADM in 1983 with a first-generation model scheduled for completion in 1986. According to NAPAP officials, interagency agreements specified that the first generation product would be evaluated and improved, if necessary, at that time. RADM's first peer review panel did suggest changes that NAPAP believed to be warranted for the assessment. The second-generation RADM, the version to be used in the integrated assessment scheduled for completion in 1987, was delivered to NAPAP in January 1989. This delay alone should not adversely affect issuance of NAPAP's integrated assessment because other task groups' products, which use RADM output, are not yet available.

In addition, a series of formal evaluations designed to reduce remaining uncertainties associated with RADM, originally scheduled for completion in 1987, is now due no earlier than 1992. NAPAP feels comfortable using RADM in the assessment, despite the model's incomplete formal evaluation, because several informal evaluations (including two peer reviews) indicate that the model's conceptual framework is sound. However, some experts still believe that the reliability of analyses involving RADM will be uncertain because of the incomplete formal evaluations. NAPAP has identified other key events remaining in RADM's evaluation process that could adversely impact the assessment and formal evaluation.

RADM's Place in the Integrated Assessment

NAPAP plans to use a variety of models to depict its current understanding of the mechanisms involved in acidic deposition and its effects. These models are an important facet of NAPAP's integrated assessment.

Energy usage scenarios will be used as inputs to the NAPAP emissions models to produce emissions patterns and cost estimates. The emissions results will be used in atmospheric models, including RADM, to provide deposition patterns. These results will then be used as inputs to effects models to produce estimates of effects, which will then be reported as conservation and health benefits. Some of the effects results will also be used as inputs to economic models producing estimates of economic effects. NAPAP officials maintain that while RADM represents one of many models being employed for the assessment, none of which is expendable, RADM's depiction of atmospheric processes makes it central to understanding the transformation and transportation of acidic deposition.

NAPAP undertook development of RADM for its integrated assessment because earlier models used to study acidic deposition were unable to represent some key atmospheric processes, including the complex chemical conversion of sulfur and nitrogen oxides into acid compounds. NAPAP

believes that an accurate representation of these processes is important for the evaluation of regional patterns of transformation and deposition, as well as for crafting effective control programs. RADM is envisioned as providing a more complete representation of atmospheric processes than previously available, incorporating the relevant science of acidic deposition. According to NAPAP, the scientific completeness of a model like RADM is required in the integrated assessment because NAPAP expects significant changes in regional pollutant concentrations during the 40-year assessment time frame.

NAPAP considers understanding the link between emissions and deposition essential, because it would enable emission control decisions to be based on accurate representations of expected effects on deposition. In the past, the Congress has considered proposals that have sought large, 10- to 12-million-ton reductions in annual SO_2 emissions without scientifically sound knowledge of the extent to which, and where, actual deposition would decrease as a result of such controls. In the current Congress bills have been introduced seeking 10- to 12-million-ton reductions in annual SO_2 emissions. Understanding the emission-deposition linkage should help the Congress structure more effective and efficient emissions control legislation.

RADM estimates of current and future levels of deposition are also critical input to understanding the extent and cost of damage caused by acidic deposition. According to NAPAP plans, effects task groups will develop "dose-response" functions,[1] which will be used with RADM estimates to approximate the extent of acidic deposition-caused damage. RADM estimates of total deposition will serve as input into effects groups' models. These models, using previously derived dose-response functions, will aggregate the total damage caused by acidic deposition. Once the extent of damage is computed, estimates of damage cost will be derived through standard econometric procedures.

NAPAP plans also call for RADM to figure prominently in addressing questions on the relationship between sources of acidifying emissions and the location of their eventual deposition. NAPAP officials told us that the effectiveness of various control scenarios may depend to some extent on regional "targeting" of controls. For example, RADM can be used to identify regions with the greatest exposure to acid compounds,[2] which can

[1]The relationship between a given level of exposure to acidic deposition and the rate of deterioration due to that exposure.

[2]"Greatest exposure" in terms of heavy deposition and/or high levels of acidity.

then be used to approximate the extent of acidic deposition-caused damage and the cost of such damage, as well as identify regions whose emissions are most acutely responsible for exposure to acid compounds.

RADM Development Milestones Have Slipped

Development of RADM began in June 1983 when EPA, working under the auspices of NAPAP's Atmospheric Transport Task Group, entered into an interagency agreement with the National Center for Atmospheric Research (NCAR) to produce a model in support of the integrated assessment. Although the original objectives and deliverables in the 1983 agreement were relatively modest, program expectations have grown since. Table 2.1 displays the evolution of these goals and slippage of milestones.

Table 2.1: Comparison of Original and Current RADM Milestones

RADM deliverable	Original milestone	Actual/projected delivery date
Project report & summary: first generation chemical module[b]	8/84	Gas-phase: 12/84 Aqueous-phase: 3/85
Engineering assessment model workshop report and technical plan	1/85	12/84
Progress report on first generation model[a,b]	1/85	Draft: 1/85 Final: 6/85
Recommendations for model evaluation procedures & data sets[a]	6/85	Included in 1984-85 working group recommendations
Report on preliminary evaluation of RADM I[a,b]	12/85	Draft: 12/85 Final: 3/86
Report on evaluation of assessment model against RADM I[b] & field data	4/86	Draft: 4/87
Project report & summary on second generation chemical module[b]	8/86	See the following
Report on RADM II[b] Chemical Module	10/86	Draft: 12/86 Final: 4/87
User's guide on testing a sulfur assessment model	8/86	Draft: 4/87
Guide for user interface with sulfur assessment model	1/87	Draft: 4/87
Final report and documentation on RADM II[a,b]	12/86	To be delivered
Final report on RADM II[b]	10/87	To be delivered
Final report on RADM II[b] project	5/90	To be delivered
Report on status of aggregation project	2/87	Final: 6/87
Report of RADM II[b] for peer review	4/87	Draft: 4/87
Report on evaluation of RADM I[a,b]	9/87	Submitted for publication: 6/87
Report on testing and evaluation of advanced version of sulfur model	10/87	Postponed on recommendation of peer review
Guide for user interface with RADM I[a,b]	12/87	Part of final project report
Overview of RADM II[b] structure with guidelines for use, structure diagrams	Draft: 7/88[c] Final: 12/88	Draft: 7/88 Final: 12/88
Complete descriptions of RADM II[b] science	Draft: 7/88[c] Final: 12/88	Draft: 12/88
Complete description of RADM II[b] computer code	Draft: 8/88[c] Final: 12/88	Draft: 7/88 Final: 12/88
RADM II[b] initial and boundary conditions	Draft: 9/88[c] Final: 12/88	Postponed
Comparison of RADM I[b] and RADM II[b] for OSCAR[d] data	2/89	Submitted for publication: 3/89
RADM II[b] sensitivity to lateral boundary conditions and initialization procedures	4/89	To be delivered

RADM deliverable	Original milestone	Actual/projected delivery date
RADM II[b] performance in aggregation studies & RADM sensitivity analyses of transboundary fluxes	5/89	To be delivered
RADM II[b] performance in nested operation	7/89	To be delivered

[a]Original program goals.

[b]The first version of RADM, referred to as "first generation" or RADM I, was completed in 1985. By mutual agreement between RADM modelers and NAPAP, a revised version, referred to as "second generation" or RADM II, was developed for the integrated assessment.

[c]These were the only milestones to have "draft" or dates for interim products established in the interagency agreements.

[d]Oxidant Scavenging Characteristics of April Rains.

Originally a documented model was to be delivered to NAPAP by January 1987.[3] In August 1986 NCAR notified EPA that it would complete the development phase of RADM but would not participate in the final evaluation. The Center considered evaluation outside its mandate to conduct research. As a result, in June 1987 at the invitation of the director of the department of atmospheric sciences, the RADM project moved to the State University of New York at Albany (SUNY-Albany) where RADM development continued.

Since the interagency agreement was signed in 1983, the number of deliverables has increased dramatically. The Director of the Acid Deposition Modeling Project (RADM's project director) stated that this proliferation of interim products helped delay RADM development and precluded providing NAPAP with the version of RADM to be used for its integrated assessment until January 1989.

NAPAP officials suggested that they may have originally underestimated the enormity and complexity of the RADM project, resulting in setting unrealistic initial milestones, which also led to slippages in RADM's development schedule. For example, while RADM estimates 3-day "episodes" of acidic deposition, effects task groups, RADM's primary users, require annual estimates to compute the damages and costs of acidic deposition. However, development of a means to aggregate RADM outputs to annual averages has proved to be more difficult than originally anticipated.

[3]Documentation of models used to assist decision makers is important because in most cases it allows others, besides the model's developers, to understand, run, and test the model. However, according to the RADM project director and the leader of the Atmospheric Transport task group, the time constraints imposed by the integrated assessment's schedule, together with the enormity of the task, have precluded complete RADM documentation. In addition, they believe that because of its immense complexity and computer requirements, even with what is typically considered complete documentation, RADM will never become a "turn-key" model.

Atmospheric Transport and Modeling Task Group staff told us in January 1989 that an acceptable approach had been developed and had passed peer review and that initial testing of the methodology would begin in February 1989, with implementation scheduled for September 1989.

RADM represents only one example of NAPAP scheduling slippages. In a 1987 report, Acid Rain: Delays and Management Changes in the Federal Research Program (GAO/RCED-87-89), we noted that NAPAP assessments and other key documents had been delayed. For example, annual reports have been issued up to 13 months late. Further, NAPAP published its interim assessment in September 1987, 21 months beyond a December 1985 date that was considered realistic by some NAPAP officials, including the official responsible for coordinating development of the 1985 assessment.

Since our 1987 report, however, NAPAP's on-time record has improved. For example, NAPAP's 1988 annual report was issued on schedule (January 1989), the first NAPAP annual report to achieve that distinction, according to the director. In addition, NAPAP published its Draft Assessment Plan, as well as its Revised Assessment Plan, virtually on schedule. NAPAP's Assessment Plan update, originally scheduled for publication in July 1989, was delayed slightly to August 1989, but only to allow NAPAP staff to incorporate the president's Clean Air Act proposal in the updated planning.

RADM Development Does Not Seem to Have Delayed the Integrated Assessment

Delays in RADM development appear to have had minimal impact on the assessment process. For example, according to senior NAPAP officials, important research in verifying current effects information (question I) and in determining current emission-deposition relationships (question II) is proceeding on schedule. Unfortunately, however, only the Aquatics Effects Task Group has estimated the dose-response functions necessary to utilize RADM output. Until the materials and forest effects task groups can reduce uncertainties in their results, they will be unable to develop scientifically defensible dose-response functions. Such functions are needed for use with RADM to make quantitative assessments of effects. Without progress from the materials and forest effects groups, it appears that these groups, rather than delays in RADM development, are more likely to represent the main limitations in the NAPAP assessment's completeness and usefulness.

Forest and Materials Effects Research Requires Additional Time for Completion

According to NAPAP's projections, some forest effects information may not be available until after the integrated assessment's release, and much of what is available will be highly uncertain. For example, central to the concern for forest resources is the still unanswered question of whether acidic deposition effects are sufficient to increase tree mortality or decrease forest health and productivity. However, projection of forest responses under various deposition scenarios is not scheduled for completion until after the assessment. NAPAP's research plan does not schedule delivery of preliminary dose-response functions for ozone, sulfur, and nitrogen compounds for individually tested trees until 1990. Significantly, these functions are not anticipated to be generalizable to forests until after the assessment. NAPAP expects that parts of the projection will be available for the assessment, but scientific confidence levels for the information will generally be low. According to NAPAP's assessment plan, "[m]any of these dose-response functions will be only recently developed and relatively uncertain." The effects of acidic deposition on forests emerged as a major research issue in 1983. This late start and the fact that seedlings require several decades to mature may be responsible for forest effects current status.

Assessing the sensitivity of man-made materials to change from acidic deposition/air pollutants is also projected to be completed relatively late in the assessment process, and like forest effects, these results are likely to be highly uncertain. The ultimate measure of damage for materials is the change in useful service life or the change in repair and maintenance costs. But developing these measures requires a basic understanding of how acidic deposition affects materials and how critical thresholds lead to material failure. However, preliminary dose-response functions for materials are not scheduled for completion until 1990.

These findings are consistent with our previous reports, An Analysis of Issues Concerning "Acid Rain" (GAO/RCED-85-13), Acid Rain: Federal Research Into Effects on Waters and Forests (GAO/RCED-86-7), and Acid Rain: Delays and Management Changes in the Federal Research Program (GAO/RCED-87-89), in which we concluded that NAPAP effects task groups had significant work remaining. Until the forest and materials effects groups can close the level of uncertainty currently surrounding their work and develop dose-response functions, RADM's potential will remain unusable to them.

RADM Analyses for the Integrated Assessment Will Be Delayed

RADM output was originally scheduled to be delivered to effects groups on October 1, 1989. The leader of NAPAP's Atmospheric Transport Task Group told us that RADM's schedule to meet the October 1 milestone has always been tight, with several important overlapping analyses and little or no allowance for delay. For example, RADM's schedule called for overlapping production runs and analyses for assessment questions II (emission-deposition relationship), III (sensitivity to change), and IV (future conditions). The Atmospheric Transport Task Group leader identified four critical milestones that had to be met if RADM production runs and analyses were to be completed on time by October 1989:

- The model had to be, and was, delivered from SUNY-Albany to the Atmospheric Transport Task Group by January 31, 1989.
- The Emissions and Controls Task Group succeeded in meeting its target date of January 31, 1989, for delivery of 1985 emissions inventory data. These data serve as baseline input for RADM analyses.
- The aggregation methodology, which allows RADM 3-day episode predictions to be annualized, had to be resolved, and was, by January 1989.
- The Emissions and Controls Task Group had to deliver emissions estimates for future scenarios (i.e., the years 2010 and 2030) by May 1, 1989.

The fact that the first three of these deadlines were met suggests that the schedule was probably reasonable.

Meeting the final milestone, however, has proved to be difficult. NAPAP plans to compare alternative future scenarios to evaluate potential environmental and human health benefits. These comparisons will, according to NAPAP, use "reference scenarios" as a common basis for comparing alternative control strategies and a set of emissions reduction scenarios that can be used to assess the implications of different levels, timing, allocation, and mix of emissions reductions. Senior NAPAP officials told us that agreement on fundamental assumptions used to develop the reference cases ran about 10 weeks late and consequently had thrown RADM's applications behind schedule.

According to NAPAP officials, a disagreement between EPA and DOE over the extent to which utilities will install cleaner coal-burning equipment, without legislation mandating such installations, was at the heart of this delay. Greater use of clean coal technologies has the potential to dramatically reduce future SO_2 emissions without specific acidic deposition control language in legislation. Thus, estimates of future emissions, critical

to RADM's depiction of future case scenarios, depend heavily on estimates of clean coal technology usage.

EPA and DOE positions on the issue are diametrically opposed. EPA believes that utilities will not adopt such technology, without legislative prodding, because there is (1) a high level of utility activity in extending the lives of older, usually high-emitting, facilities and (2) substantial doubt that state public utility commissions would agree to allow utilities to recoup the costs of major clean coal investments through increased rates unless required by law or regulation. As an example, EPA noted that utilities have placed virtually no orders for clean coal equipment outside DOE-subsidized demonstration programs. Conversely, DOE's position is that utilities will, to a large extent, adopt clean coal technologies once the process is proven to be competitive in the marketplace.

Senior NAPAP officials expressed concern that unless the feuding agencies resolved their impasse, timing of the integrated assessment could be adversely affected. On May 17, 1989, EPA and DOE negotiators reached an agreement, in principle, regarding the clean coal question. The details of implementing the agreement were negotiated May 23, 1989. NAPAP believes that through this agreement, a major obstacle in producing a quality, on-time assessment has been overcome.

Although a significant amount of analysis time has been lost to the disagreement, NAPAP officials noted that RADM runs have been sequenced and overlaid to attempt to minimize the effects. NAPAP officials now believe that RADM output can be delivered to effects groups in two stages. The first, due in December 1989, will include sulfur-only analyses of the 2010 reference case. The other set of RADM output, which should become available in February 1990, is supposed to encompass sulfur and limited multiple pollutant analyses for the 2030 reference case. NAPAP officials remain confident that the assessment can be completed by September 1990. The fact remains, however, that RADM's milestones remain extraordinarily tight and that questions remain on whether future emissions estimates will be provided on time. Senior NAPAP officials asserted that while any further delays could jeopardize the overall timing of the integrated assessment, they believed that the situation was under control and that the Atmospheric Transport Task Group will deliver RADM output in accordance with the revised schedule.

The Atmospheric Transport Task Group leader anticipates few problems meeting the new RADM production milestones, although some RADM-assisted analyses will probably have to be curtailed. In particular, as we

discuss in chapter 3 of this report, RADM is uniquely suited to depict the effects of multi-species control programs on acidic deposition. Yet, as a result of lost analysis time due to the EPA-DOE impasse over emissions estimates, the Atmospheric Transport Task Group chairman is uncertain whether in-depth studies that involve NO_x and hydrocarbon emission changes can now be completed for inclusion in the integrated assessment. While this is not expected to dramatically affect the quality of the assessment, the chairman noted the irony in developing a model designed precisely to handle such conditions and then being unable to complete the required analyses for lack of timely input data.

RADM Evaluation Process

In September 1988 NAPAP published a draft protocol for evaluating RADM. The objectives of this formal evaluation are to assess and establish the credibility and limitations of RADM and to identify and delineate needs for development and refinement. In addition, RADM has undergone a significant amount of testing outside the formal evaluation process.

NAPAP's Formal Evaluation of RADM

The draft protocol for evaluating RADM calls for two basic types of evaluation:

- operational evaluation, which is an attempt to determine the accuracy of the model's deposition estimates, and
- diagnostic evaluations, which are tests against laboratory and field data to ascertain the extent to which the model represents the science of acidic deposition as it is currently understood.

One senior NAPAP manager described the process as "... checking to see if the model is right [operational evaluation], for the right reasons [diagnostic evaluations]."

The operational evaluation will compare RADM's estimates of acidic deposition, wet and dry, against actual measured levels of deposition. To perform the operational evaluation, NAPAP must first measure surface deposition, then compare RADM estimates with measured deposition. As of June 1988, NAPAP, working in cooperation with EPA, the Electric Power Research Institute, the Atmospheric Environment Service of Canada, and the Ontario Ministry of the Environment, had four coordinated surface monitoring networks to collect and measure levels of deposition. These networks consist of more than 100 sites distributed across eastern North America. According to one NAPAP official, results from these latest data collection efforts became available in March 1989.

NAPAP has also begun a series of aircraft measurements designed to obtain atmospheric data aloft. The first of the series was conducted between August 15 and October 7, 1988. These data can be used to provide chemical measurements so that measured concentration patterns can be compared with RADM predictions. Analysis of these airborne measurements is intended to assess the model's ability to accurately depict the chemical and physical processes that create and transport acidic deposition. The intention in this phase of the evaluation is to "stress" the model, that is, to test those elements in the model most sensitive to a correct understanding of the atmospheric phenomena that result in acidic deposition.

NAPAP officials acknowledge that while many scientists are now confident of RADM's abilities, there remain RADM skeptics within the scientific community, and that several years of study carrying through the evaluation will be required to generate more widespread acceptance. For example, they told us that a scientifically complete evaluation of RADM is not possible prior to release of the assessment and that at least until the evaluation is complete, some scientists would continue to question the model. In order to help meet these concerns, a second intensive data gathering campaign was scheduled for fiscal year 1989 with analysis of these and other data gathered from airborne and surface stations continuing into 1992. At that time NAPAP officials believe RADM will have been thoroughly evaluated and will have gained high levels of acceptance among scientists.

Informal RADM Evaluation

The Deputy Director of EPA's Office of Environmental Processes and Effects Research told us that RADM has already undergone more extensive testing than any model currently in EPA's stable of models. For example, in addition to the evaluation analyses described above, RADM has undergone two peer reviews by scientists not involved with development of the model to determine whether RADM was based on sound, reasonable judgments supported by the best available scientific knowledge. In the first review, conducted during March 1985, the panel concluded that RADM promised major improvements in regional model performance and reliability, if the model was fully developed. The second review panel concluded in May 1987 that RADM development had been an impressive achievement, likely to ensure that RADM would be at the forefront of scientific capabilities. The second panel also noted that RADM should provide the basis for addressing with scientific confidence many of the important questions concerning acidic deposition and its control.

As a first step in evaluating the ability of RADM to simulate measurements of deposition, RADM estimates were compared to observations made in three episodes of the Oxidation Scavenging Characteristics of April Rains (OSCAR) program. The chemical concentrations in rainfall and deposition of sulfate and nitrate, as well as rainfall amounts, were observed at up to 36 sites, at three different points in time (OSCAR-I, -II, and -IV). OSCAR observations were compared to the corresponding RADM estimates. For OSCAR-I and -IV, it was found that estimated and observed sulfate and nitrate wet deposition generally agreed, to within a factor of 1.6. Good agreement was found between the regions of highest estimated and observed deposition and in areas where rainfall was reasonably well estimated. The results for OSCAR-II were less conclusive and are subject to continued investigation. The degree to which RADM's averaged rainfall patterns are representative of the point measurements is believed to be a factor affecting the accuracy of the model's predictions.

Across all OSCAR events, agreement within a factor of 2 between modeled and observed deposition was generally noted. The best agreement was found for sulfate deposition. Discrepancies between model estimates and observed deposition were found to be the result of inaccuracies in RADM's precipitation estimates.

In addition, RADM's creators have published more than 80 articles in scientific journals describing and demonstrating the complete model or its various components. These publications represent a kind of peer review in their own right because such articles are critically reviewed by experts prior to publication. According to RADM's project director, RADM articles frequently draw six reviewers rather than the customary three. While acceptance for publication is not synonymous with scientific acceptance, the extensiveness of this list of publications does indicate that the model is being heavily evaluated in the scientific community.

Challenges Still Confront RADM Evaluation

RADM's evaluation timetable may pose problems for assessment activities. For example, final evaluation of RADM is required to confirm NAPAP's conclusions drawn in the integrated assessment. The probability that these conclusions would require reexamination seems remote at this time because of the extensive testing already done and planned prior to the assessment. However, since NAPAP's assessment production schedule calls for RADM deposition estimates prior to the time when the evaluation

will be completed, a small chance remains that RADM may be found lacking without sufficient opportunity to implement improvements for the assessment.

NAPAP officials also faced critical decisions regarding resolution of problems brought about by a contractor cost overrun on the surface monitoring network. NAPAP officials told us that the primary contractor on the surface network had a first-year overrun of approximately $2.5 million on a contract worth about $17 million. Aside from the quite substantial financial questions such an overrun portends, the potential effects on the timing and quality of RADM's evaluation and the assessment itself are daunting. NAPAP officials reprogrammed money from a number of sources within EPA to cover the overrun. The reprogrammings came from three sources: (1) $1 million from funds within the discretion of the director of the Atmospheric Research and Exposure Assessment Laboratory (AREAL), (2) $0.5 million from EPA headquarters accounts, and (3) $0.8 million from other laboratory programs. In addition, according to the Atmospheric Sciences and Research Laboratory (ASRL) director, who was in charge of NAPAP's response to the overrun, NAPAP completely shut down its surface monitoring activities until the situation could be brought under control. This may have had an adverse impact on the timing of RADM's evaluation, but the director is convinced that consequences would have been much worse had the previous situation been allowed to continue. Currently, NAPAP has reinstituted all surface monitoring activities and has experienced no further cost overrun problems.

Senior NAPAP officials do not believe that these measures will have a major adverse impact on the assessment. The AREAL director has been instructed to make only reductions that would not directly affect the assessment. A senior EPA manager plans to review AREAL reprogrammings with the specific intent of ensuring that the assessment activities are not harmed. The EPA headquarters funds marked for redirection were not devoted to assessment activities. NAPAP does expect that laboratory reprogrammings will affect the research program over the long term, and that one reduction, on Colorado dendrochronology,[4] if implemented, could have a small direct impact on the assessment. Laboratory directors have been requested to review reprogrammings affecting their programs to determine whether impacts on continuing programs or on the assessment could be further minimized. Preliminary indications are

[4]The science of dating events and variations in environment in former periods by comparative study of growth rings in trees and aged wood.

that a redirection of funds from the Colorado forestry study can be avoided.

According to the ASRL director, adverse effects of the overrun have been kept to a minimum. Thus far, only the second intensive data gathering effort, rescheduled from fiscal year 1989 to fiscal year 1990, has been affected. The director warned, however, that it is too soon to estimate the total effects of the overrun.

Conclusions

Model development for the integrated assessment is complete, with RADM now available to NAPAP applications groups. RADM's delivery was delayed, at least in part, by expansions in NAPAP's list of interim products. In addition, the RADM project as a whole became more complicated than first envisioned, rendering original milestones unattainable.

NAPAP delays in bringing the model on-line do not appear to have adversely affected the assessment because an inability to estimate dose-response functions for forests and materials, and the lateness of future emission estimates, seem to have negated the impact of RADM's tardiness. If the Atmospheric Transport Task Group can meet its admittedly tight assessment support schedule, then RADM output should be available to effects task groups by the revised milestone dates of December 1989 and February 1990.

Evaluation of RADM is essential to establish its credibility as a tool useful in atmospheric science and NAPAP's integrated assessment. While RADM now appears to be well short of being completely evaluated, and a level of uncertainty exists regarding its conclusions, the model has already been through a significant amount of testing. Contractor problems on the surface monitoring network have required EPA to reprogram money from several sources to cover a RADM shortfall and could yet adversely affect the timing of RADM's formal evaluation. According to a senior EPA manager, RADM remains the most thoroughly tested model in EPA's inventory of models. Confidence in RADM appears to be high.

Value of RADM in Emissions Control Decisions

Simpler models are not capable of correctly reproducing three kinds of complex features that may be important in polluted atmospheres. RADM, which was designed specifically to address these complexities, should produce results worthy of consideration before large-scale emission control decisions are reached. However, decisions on moderate-sized emission controls involving reductions in SO_2 emissions only, which were the first stage of a larger emission reduction program, could be made without waiting for RADM results. At this time some scientists still doubt whether RADM will be capable of the improvements claimed for it. More comprehensive RADM results and a completed evaluation of the model should be available before actions on larger scale emission controls have to be taken.

Justification for Using RADM

RADM models certain complex features of the atmospheric processes that affect the chemistry and transport of air pollutants contributing to acidic deposition, features that cannot be properly treated by preexisting, simpler models.

Simple models of these atmospheric processes have been applied to North America for about a decade. However, several features of the atmospheric phenomena that contribute to acidic deposition may result in complexities that the simpler models do not take adequately into account. These features involve

- the adequacy of the supply of certain chemical substances, called oxidizing agents or oxidants, in the atmosphere;
- the geographic range of transport of acidic or acidifying substances, and the interaction between transport distance and transformation and deposition; and
- the involvement of some of the same chemical substances in acidic deposition and in other pollution processes, so that emission controls aimed at one kind of pollution might adversely affect another pollution problem.

Supply of Oxidants

Acidic deposition of sulfur-containing material involves both dry deposition, which is predominantly in the same form, SO_2, as it is emitted, and wet deposition, in which the sulfur is in the form of sulfate or sulfuric acid. The transformation of SO_2 (or its equivalent in water, sulfurous acid) into sulfate is a type of reaction called an oxidation. It is accomplished in the atmosphere by reaction of the SO_2 with one or another of the three highly reactive oxidizing substances or oxidants: hydroxyl

radical in free air, or hydrogen peroxide, or possibly ozone in cloud water. If supplies of these oxidants in the atmosphere (or a region of it) are limited, then there would not be as much sulfate formed there from SO_2 as would occur with an unlimited oxidant supply, and more SO_2 in that portion of the air would remain unoxidized. In an oxidant-limited situation of this kind, sulfate deposition in precipitation would be less than proportional to SO_2 emissions, a situation sometimes referred to as "nonlinearity."

There has been some concern about oxidant limitation and its effects on the relationship between emissions and deposition. This has sometimes been expressed in an oversimplified fashion. For example, a recent statement said, "Reducing emissions by a given amount may not yield a proportional reduction in the acidity of precipitation."[1] While this statement is technically correct, it is misleading because it omits recognition of the occurrence of dry deposition. In fact, the SO_2 not converted to sulfate due to oxidant limitation in one geographical area remains in the atmosphere available to be dry deposited there or elsewhere, or to be oxidized and deposited in precipitation at a different location if it meets new oxidant. Whether this would result in total acidic sulfur deposition at the first location being lessened,[2] remaining the same, or even being increased due to a balancing increase of dry deposition, is not immediately clear. Use of the RADM, which can take all of these possibilities into account, would make it possible to follow emitted material to whichever of these fates it meets.

Oxidant limitation is not only a hypothetical possibility. It has been observed that even though eastern U.S. SO_2 emissions remain about the same all year round, there is less SO_2 and more sulfate found in our atmosphere in summer than in winter. This occurs because the supply of oxidants in the atmosphere is less in winter than summer.[3]

[1] "Reality Test for Acid Rain Models," EPRI Journal, Vol. 13, No. 8, (Dec. 1988), p. 29.

[2] Total acidic sulfur deposition, rather than sulfate in precipitation alone, is the key variable to measure because acidic deposition researchers generally regard the two forms of sulfur deposition, SO_2 and sulfate, as contributing equally to damage. This is largely because SO_2 deposited unoxidized is rapidly converted to sulfate after deposition.

[3] The lessened oxidant supply occurs because the principal sources of atmospheric oxidants are reactions caused by ultraviolet light, less of which strikes the atmosphere in winter when days are shorter and sunlight arrives at a shallower angle than in summer.

Transport Distances and Their Interaction With Transformation and Deposition

A main purpose for modeling the atmospheric phenomena involved in the acidic deposition process is to be able to better understand source-receptor relationships, that is, to tell, for material deposited at one location (referred to as a receptor), which source or sources it was emitted from. To do this it is necessary to be able to tell the distances pollutants travel from where they are emitted to where they or their transformed products are deposited. While these distances clearly depend on the air movements that carry pollutants, they also can differ depending on the form the substance takes. Approximate estimates of mean transport distances are 1,280 to 2,400 kilometers (km) for sulfate, compared to only 480 km for SO_2. These very different distances for different forms of sulfur mean that the total distance over which emitted SO_2 travels before deposition will be strongly affected by whether—and, if so, when—it gets oxidized.

The length of these mean transport distances shows that SO_2 emitted at any location will spend up to several days in the atmosphere, with the material that stays aloft longer having a much greater chance to mix with air originating from other areas, which could contain different proportions of pollutants. This can allow the material to undergo slower, or more rapid, chemical transformations than if it had remained in the original air sample into which it had been emitted. For example, a sample of emitted SO_2 could find itself in oxidant-limited conditions when first emitted and later get more fully oxidized upon mixing with other air that contained more oxidant or oxidant precursors.

Realistic modeling of these complex interactions between transport, transformation, and deposition requires a model such as RADM that is capable of including such complexity. In fact, such a situation involving interaction between transport distance and oxidant supply was successfully modeled in a study carried out using a version of the RADM model. The study used the model to simulate the behavior of the eastern North American atmosphere in several spring and summer episodes of which field studies had been done several years earlier. In the study NAPAP scientists found situations in which oxidant limitation occurred near SO_2 emission sources, but oxidant limitation decreased farther downwind.

Complex Interactions Among Air Pollutants

Acidic deposition is only one of several pollution processes that arise from a limited set of emitted substances. Some of these substances are common to more than one process, linking them so that an action aimed at controlling one process may affect others also.

SO_2 and NO_x emissions are the precursors of the sulfuric and nitric acids that are the acids in wet acidic deposition with a contributory role also played by oxidants. However, besides being the source of the nitrogen in nitric acid, NO_x emissions are also involved in reactions with volatile organic compounds that lead to formation of another pollutant, ozone. Ozone, in turn, is a strong oxidant that is involved, by its participation in the production of hydroxyl radical, and also perhaps directly, in the oxidation of the acidic deposition precursors, SO_2 and NO_x. Further dimensions of complexity are added by the fact that the other main precursors to the formation of ozone, besides NO_x, are volatile organic compounds, and that most of the above components and others also participate in aerosol (particulate) formation.

The significance for the acidic deposition issue of this set of interrelations among air emissions derives from ozone being the pollutant that most often remains in a nonattainment status; i.e., it occurs in amounts exceeding the National Ambient Air Quality Standards in much of the United States.[4] NAPAP staff involved in modeling work told us that this means ozone is likely to be the subject of substantial control efforts in the coming decades. If efforts at ozone pollution control are successful, they explained, then the supply of oxidants in the U.S. atmosphere may be diminished substantially. This, in turn, could leave less SO_2 oxidized to sulfate and more as SO_2, which in light of the different transport distances noted above would change the range of transport of acidic materials and thus alter source-receptor relations.

Interplay of Atmospheric Phenomena

The interplay of these three sets of factors—oxidant supply, differing transport ranges, and complex interactions—gives rise to many possibilities for complicated atmospheric phenomena that may need to be taken into account for an adequate representation of the acidic deposition process.

It is not necessarily true that these complex features will control or strongly influence the actual processes in the current atmosphere. However, RADM's project director told us that, to model these phenomena in a scientifically valid way, it is necessary to use a model that includes all the possible complexities. Then, he explained, if these features are important, their roles will be modeled properly. If instead the complex

[4]Under the Clean Air Act, EPA has been required to establish national ambient air quality standards, maximum allowable concentrations to avoid harm to public health and welfare, for six air pollutants: ozone, SO_2, NO_2, particulate matter, carbon monoxide and lead.

model shows that the complexities and possible nonlinearities are not significant, it will be scientifically convincing evidence that older, simpler models can be used, at least for the current atmosphere.

Furthermore, the U.S. atmospheric pollution situation in the next two to four decades, even if there were no acidic deposition control actions taken, is likely to see reduced oxidant levels due to ozone control policies and actions that should be developed and implemented in the coming years to try to overcome the nonattainment situation noted above. As a result, there is a greater possibility of seeing oxidant-limited atmospheric conditions influencing the behavior of acidic deposition pollutants in nonlinear ways in the future than at present. Therefore, it would be necessary to use a model like the RADM to describe the behavior of the atmosphere in the future, under the differing scenarios to be examined in the NAPAP assessment.

Limits on the Potential Contribution of RADM to Modeling Deposition

Some scientists involved in acidic deposition atmospheric research and modeling are less optimistic about the promise of RADM than the official view presented above, regarding limits to RADM's accuracy. These limits may come from the model itself, from uncertainty in the data put into it, or both.

Uncertainty of input data is generally recognized to be greatest in the speed and direction of winds that provide the transport field—it is based on upper air wind observations made only twice daily at widely scattered sites. There is also significant uncertainty in emissions data, since most of such information is estimated from emissions factors rather than measured in actual observations.

Contributions to uncertainty from the model itself include a recognizedly incomplete treatment of the way clouds behave in absorbing and depositing pollutants and the smoothing-out of both input and output that necessarily occurs when the unit of analysis is an individual grid square of 80 kilometers (50 miles) on a side. The author of a review article has expressed doubt that RADM can be successful even in 5 years, due to internal uncertainty.[5]

In addition to perceived limitations in RADM's accuracy, some scientists believe linear models provide an adequate depiction of acidic deposition,

[5]. G.E. Gordon, Environmental Science & Technology, Vol. 22, p. 1139, (1988).

thus further limiting RADM's usefulness. For example, the Regional Modeling Subgroup of the United States-Canadian Memorandum of Intent on Transboundary Air Pollution studied the accuracy of eight linear regional-scale models in depicting concentrations and depositions of sulfur compounds as well as source-receptor relationships. Generally the subgroup found these models able to depict the correct order of magnitude of the large time and space-scale features of measured wet sulfur deposition patterns. And although the subgroup concluded that it is a matter of individual scientific judgment whether linear sulfur models represent a reasonable approximation of acidic deposition in the absence of operational nonlinear models,[6] it is not clear that nonlinear effects would invalidate the general results of the linear models.

The Atmospheric Transport Task Group leader acknowledges the accuracy limitations of RADM, which he suggests may mean that estimates can be accurate only to within about a factor of two. However, he points out that the key contribution of RADM will be in sensitivity studies showing how transport and deposition compare in the same situation with only certain emission contributions changed, but all other variables kept the same. He contends that RADM will be much more accurate as a tool for examining such differences than it may be for making absolute deposition estimates.

RADM's Role in Emission Control Decisions

RADM offers definite advantages over simpler models for modeling the results of emission control actions. Experts in atmospheric modeling told us this was particularly true for substantial SO_2 emissions reductions, such as 8- to 12-million-ton overall targets and/or reductions of several kinds of pollutants at the same time ("multi-species" reductions). In contrast, we found a consensus among the experts we consulted that moderate- sized reductions of SO_2 emissions only, 25 percent or less (about 3 to 5 million tons of annual SO_2 emissions), carried out as the first phase of a larger emissions control program, need not await RADM results or evaluation or the integrated assessment. According to the Atmospheric Transport Task Group leader, the latest NAPAP research indicates that in a limited SO_2 emissions reduction scenario, linear models do not introduce an unacceptable amount of error. Hence, current air quality models should suffice to guide an interim control program of such magnitude.

[6]The results of the Subgroup were published in October 1983 before the first-generation RADM became operational in 1985.

Interim SO_2 Reductions Possible Without RADM Results

If the Congress decided to adopt a two-stage emissions reduction program, similar to those proposed thus far in the 101st Congress, then depending on its size, composition, and objectives, the first stage could be designed and carried out without necessarily requiring the use of RADM. The exact size and detailed geography of the final stage could be adjusted at a later date, taking advantage of the results of the integrated assessment and a fully evaluated RADM. At that time there might also be a prospect of having significant improvement in the quality of information on materials and possibly also forest damage.

RADM's greatest strengths and its intended purposes in NAPAP's integrated assessment are to depict possible nonlinearities in the relationship of emissions to deposition, to specify source-receptor relationships, and to account for the effects of multiple forms of atmospheric pollution in the creation of acidic deposition. NAPAP believes understanding these processes is essential to developing an effective and efficient acidic deposition control program. However, according to senior NAPAP officials, there are limited, fairly specific conditions under which a first stage of SO_2 emissions reductions might be done without utilizing RADM. Specifically, an SO_2reduction of about 25 percent (4-5 million tons) or less is not a particularly complicated or large alteration of the current atmosphere and thus would not require RADM's complex depiction of atmospheric processes in order to be scientifically defensible if it were to include SO_2 only. In contrast, any emissions reduction, regardless of size, would require RADM-assisted analysis to depict its effect on deposition if multiple pollutants are targeted for control. In a two-stage SO_2 program, an emissions reduction aimed at being about one-half the size of the one eventually envisioned would not pose a significant risk of being inappropriately large for any region targeted for controls. Omitting RADM analysis from a first-stage SO_2reduction could be acceptable as long as the primary interest is in mapping the potential reductions in deposition resulting from the full range of controls from all phases of the control program, rather than those benefits specific to interim controls. This is because if "oxidant-limits," or nonlinearities, are present in the atmosphere, they are most likely to appear in the first stage of a reduction program. While emissions controls of any magnitude in such a situation are not likely to achieve a fully proportional reduction in wet deposition, NAPAP scientists agreed that benefits would occur, especially in reducing dry deposited SO_2. In this situation RADM's capabilities would be required only to the extent that the Congress (or EPA) would like to understand how deposition responded to interim-phase emissions controls. If, however, policy makers are more interested in the larger, complete set of

emissions controls in latter phases of the control program, then RADM-based analysis of first-stage results would be much less critical.

An additional feature of a moderate, first-stage emissions reduction in the current context of doubt about the details of the relationship between emissions and deposition is that it could contribute valuable knowledge about how deposition responds to emissions reductions. Knowledge of this kind, obtained from a first-stage emissions reduction, could make a useful contribution to helping guide subsequent emissions reduction decisions. This educational contribution from an early, moderate emissions reduction was reportedly a key rationale that led a former EPA Administrator in 1983 to recommend a similar program as his preferred option for acid rain control policy.[7]

Comprehensive SO_2 Reductions or Multi-Species Reductions

In the case of a large SO_2 emission reduction or a multi-species reduction it would be preferable to have the RADM's complex modeling capacities available to analyze the results of proposed policies before they are put into effect to avoid being surprised by policies that did not accomplish their intended goals. Also, in the event of a staged emissions reduction program, the evaluation of RADM should be completed before final steps need to be taken in later stages of the program.

RADM offers a tool for planning a large SO_2 emissions reduction program—to take account of possible nonproportionality between emissions changes and acidic deposition changes, and to obtain a better understanding of source-receptor relationships. Also, the connection between the ozone pollution problem and the supply of oxidant in the atmosphere is an important reason why the use of more complete atmospheric modeling of the kind the RADM was designed to perform would be desirable before undertaking an acidic deposition policy involving a multi-species emissions control program reducing SO_2 emissions and also NO_x and/or hydrocarbon emissions.

The ozone system itself is very complex. Depending on relative proportions of volatile organic compounds and NO_x pollutants in the atmosphere, there are some conditions in which reducing NO_x emissions can decrease ozone formation and others in which reducing NO_x emissions can increase ozone formation. It could thus be possible, for example,

[7] A similar argument for the value of knowledge to be gained from observing the results of early emission control steps has also been made in a recent scientific review of the acidic deposition process. See S.E. Schwartz, Science, Vol. 243, p. 761 (10 February 1989).

that a strategy of lowering both SO_2 and NO_x emissions, each of which would be intended to lower acidic deposition, could inadvertently increase ozone pollution both by affecting hydrocarbon/NO_x proportions and by lowering oxidant consumption. Similarly, emissions reductions of NO_x and/or volatile organic compounds, intended to reduce ozone formation, could affect oxidant supply and therefore the proportions of wet versus dry acidic deposition and their geographic distribution. All of these complex possibilities are reasons why, in order to have an accurate and surprise-free understanding of the results of a multi-species emissions control program, it would be desirable to be able to analyze proposed programs in advance with an atmospheric model having the full design capabilities of RADM.

Furthermore, questions about the validity and accuracy of RADM should be answered before the date when a second phase of a two-phase or multi-phase emissions reduction program would start. Such proposals tend to leave the second stage to the mid-90s or later, while RADM's evaluation is targeted for completion by 1992 or possibly 1993, allowing for some further slippage in schedule.

Conclusions

The overall reason for using RADM is to be able to properly represent atmospheric processes, both now and in the future. If this is done, then—if and when emissions control policies are instituted—it should be possible to estimate with greater accuracy than previously possible what changes in deposition will result. This will mean that better connection can be made from control costs to deposition changes and thence to damage reduction. As a result, decisions on emissions control actions can be based on a knowledge of how much damage avoidance or environmental protection will be obtained from a particular emissions control action.

This reasoning explains why it would be worthwhile to use RADM to model the effects of a large SO_2 emission reduction or a multi-species emission reduction before carrying out the emissions reduction program. In contrast, a moderate-sized program involving SO_2 emissions reductions alone, if carried out as a first stage of a larger program, could be initiated without waiting for modeling by RADM without risking excessive or unnecessary control actions.

NAPAP Organization

The task force that implements the National Acid Precipitation Assessment Program is jointly chaired by the Environmental Protection Agency (EPA); the Departments of Agriculture (USDA), Energy (DOE), and the Interior (DOI); the National Oceanic and Atmospheric Administration (NOAA); and the Council on Environmental Quality. Other statutory members include the Department of Commerce, the Department of Health and Human Services, the Department of State, the National Aeronautics and Space Administration, the National Science Foundation, and the Tennessee Valley Authority. The task force includes four presidential appointees as well as representatives from DOE's Argonne, Brookhaven, Oak Ridge, and Pacific Northwest National Laboratories.

Appointed by the Joint Chairs Council, the NAPAP Director is responsible for program planning, management, and coordination and for recommending research and assessment initiatives to the Joint Chairs and the task force. The participating agencies work with the NAPAP Office of the Director at several levels. The Interagency Science Committee, comprised of senior scientific managers from each agency, works with the director and his staff to develop, implement, and evaluate programmatic research, assessment, and budgetary requirements. The Interagency Policy Committee, comprised of senior policy officials from the agencies, is responsible for the review of NAPAP research and assessment activities to ensure that they are fully responsive to policy needs.

NAPAP's program of research is divided among seven task groups dealing with virtually every aspect of the acidic deposition issue. Senior scientists from the funding agencies are appointed by the director and the Interagency Science Committee to serve as task group leaders. These individuals are responsible for the direct oversight of NAPAP research and assessment activities. Table I.1 shows lead agencies and program responsibilities of each NAPAP Task group.

Table I.1: NAPAP Task Groups and Responsibilities

Task group	Lead agency	Responsibility
Emissions & Controls	DOE	Develop a data base containing past, present, and anticipated emissions that influence acidic deposition; devise methods to estimate the effects and costs of control strategies.
Atmospheric Chemistry	NOAA	Determine how SO_2 and NO_x emissions combine and chemically change into acidic deposition.
Atmospheric Transport	NOAA	Estimate the transport of acid compounds through atmospheric and climatic models.
Atmospheric Deposition	DOI	Develop a nationwide program to monitor the chemical composition of wet and dry atmospheric deposition.
Terrestrial Effects	USDA	Determine the extent of, and acidic deposition's role in, damage to forests and other terrestrial resources—soils, vegetation, and crops.
Aquatic Effects	EPA	Determine acidic deposition's effects on lakes, streams, groundwater, and aquatic life; develop methods for restoring acidic lakes.
Materials Effects	DOI	Determine acidic deposition's role in damage to exposed materials, and develop methods to protect these materials from further damage.

Scientific Confidence Levels in the Assessment Reports

NAPAP will use a standardized reporting method to aid in the description of uncertainties in scientific findings and assessment conclusions. NAPAP predicts that this method, with obvious analogy to a restaurant rating guide, will help identify which findings and hypotheses are well grounded (the three- and four-star cases) and which are highly questionable (the zero-through two-star cases).

Table II.1: Uncertainty Analysis ("Confidence Levels") **In State of Science/ Technology Reports and Integrated Assessment**

Code	Explanation
0	No basis for an answer
*	Some information, but major uncertainties and knowledge gaps
**	Adequate information, but generally large and ill-defined uncertainties
***	Ample information with well-defined but sometimes large confidence intervals
****	Substantial amount of consistent information

According to NAPAP, the "star ratings" are intended to communicate consensus of understanding among the specialists, relative to each finding. The ratings will appear in the review drafts of each report and will help focus debate among scientists on the credibility of key findings. Where necessary, NAPAP's final reports will describe unresolved disagreements on confidence levels to aid the use of technical information by the Congress and other policy officials.

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